Electromechanical Performance of CORC® Cables and Wires under Axial Tension and Transverse Compression

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CORC® magnet cables and wires

**CORC® wires (2.5-4.5 mm diameter)**
- Wound from 2-3 mm wide tapes with 30 µm substrate
- Typically no more than 30 tapes
- Highly flexible with bending down to < 50 mm diameter

**CORC® cable (5-8 mm diameter)**
- Wound from 3-4 mm wide tapes with 30-50 µm substrate
- Typically no more than 50 tapes
- Flexible with bending down to > 100 mm diameter
Application of transverse compressive load

Measurement under transverse compressive load
• Load applied by two flat stainless steel anvils
• Load applied at 76 K in liquid nitrogen

The flat anvils will result in a line contact with the round conductor

Effects to be studied

Model CORC® samples
• Effect of gap spacing between tapes
• Effect of copper plating thickness

Practical CORC® cables and wires
• Effect of former size and substrate thickness
• Overall behavior of practical CORC® magnet cables and wires

Transverse compressive load is especially important for larger magnet systems in which multiple CORC® cables or wires are combined into a CICC
Model CORC® samples: Effect of gap spacing

Model CORC® sample
- Hand-wound
- **Solid stainless steel former**
- 3 layers, 6 or 9 tapes
- **No epoxy impregnation!**
- Gap spacing 0 or 1 mm
- Copper plating 5 µm thick

0 mm gap spacing

1 mm gap spacing

Imprint from underlying layers are clearly visible

Larger gaps cause degradation at lower loads
Model CORC® samples: Effect of copper thickness

Critical load decreases with copper plating thickness
Critical load decreases with gap spacing

Critical stress can’t be calculated yet, because the contact with is unknown

Critical load [kN/m]

<table>
<thead>
<tr>
<th>Decrease</th>
<th>20 µm copper plating Gap spacing:</th>
<th>5 µm copper plating Gap spacing:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>1%</td>
<td>250</td>
<td>200</td>
</tr>
<tr>
<td>3%</td>
<td>260</td>
<td>200</td>
</tr>
<tr>
<td>5%</td>
<td>270</td>
<td>220</td>
</tr>
</tbody>
</table>
Transverse Compression on CORC® cables

CORC® cable layout
- Machine-wound
- 4.9 mm thick copper former
- 9 tapes wound in 3 layers
- Tapes with 50 µm substrate
- 0.1 or 0.3 – 0.4 mm gap spacing

The samples tested are production cables with annealed copper formers, instead of R&D cables with hard stainless steel formers. Larger gaps cause a decrease at lower loads, and the deformation of the former likely causes the more gradual decrease in $I_c$ with load.

Critical load decreases with gap spacing
Decrease in $I_c$ is more gradual
Transverse Compression on CORC® wires

**CORC® wire layout**
- Machine-wound
- 2.55 mm or 3.2 thick copper former
- 12 or 27 tapes
- Tapes with 30 µm substrate
- 0.3 – 0.4 mm gap spacing

<table>
<thead>
<tr>
<th>( I_c ) decrease</th>
<th>CORC®-C1</th>
<th>CORC®-C2</th>
<th>CORC®-W1</th>
<th>CORC®-W2</th>
</tr>
</thead>
<tbody>
<tr>
<td>3%</td>
<td>207</td>
<td>124</td>
<td>115</td>
<td>217</td>
</tr>
<tr>
<td>5%</td>
<td>255</td>
<td>160</td>
<td>133</td>
<td>243</td>
</tr>
<tr>
<td>10%</td>
<td>340</td>
<td>226</td>
<td>163</td>
<td>284</td>
</tr>
</tbody>
</table>

The former size in combination with substrate thickness plays an important role when considering onset of degradation under transverse load. Explanation why follows on next slide...
Effect of winding strain on CORC® performance

Winding strain in CORC® cables and wires
- CORC® wire with 2.55 mm former and 30 μm substrate: -1.16 %
- CORC® wire with 3.2 mm former and 30 μm substrate: -0.93 %
- CORC® cable with 4.9 mm former and 50 μm substrate: -1.0 %

Critical winding strain -1.25 %

Critical transverse compressive load depends on initial strain state of REBCO layer
Compressive load increase strain state toward irreversible limit
First estimate of critical transverse stress

Width of contact area determined by pressure sensitive paper

- Fixed applied load of 200 kN/m
- Average width of contact area between 0.9 and 1.16 mm

Critical load [MPa]

<table>
<thead>
<tr>
<th>( I_c ) decrease</th>
<th>CORC®-C1</th>
<th>CORC®-C2</th>
<th>CORC®-W1</th>
<th>CORC®-W2</th>
</tr>
</thead>
<tbody>
<tr>
<td>3%</td>
<td>230</td>
<td>138</td>
<td>99</td>
<td>241</td>
</tr>
<tr>
<td>5%</td>
<td>283</td>
<td>178</td>
<td>115</td>
<td>270</td>
</tr>
<tr>
<td>10%</td>
<td>378</td>
<td>251</td>
<td>141</td>
<td>316</td>
</tr>
</tbody>
</table>

Contact area likely grows with load when the conductor deforms and should be verified at all relevant loads when converting to stress.

Critical transverse compressive stress > 230 MPa in optimized CORC® cables and wires
Effect of transverse compressive load cycling

**Test procedure for cycling in liquid nitrogen**
- Each sample is loaded to peak load responding to predetermined $I_c$ retention: 95 – 97 %, 90 %, and 80 %
- Load cycled between 10 % and 100 % of peak load

Peak load with $I_c$ retention > 95 %: No significant additional $I_c$ degradation after 100k cycles
Peak load with $I_c$ retention < 90 %: Additional $I_c$ degradation after 100k cycles < 5 – 10 %
Axial tensile stress setup

**Testing CORC® wires with copper former**
- Test machine capacity = 13 kN
- Load applied through current injection terminals
- Monotonic and cyclic stress applied in liquid nitrogen

Axial stress as a result of Hoop stress is an important factor to consider when designing high-field magnets.
Monotonic axial tensile stress test results

Sample details
• CORC® wire with 30 tapes
• Solid annealed copper former of 2.55 mm diameter

Onset of $I_c$ degradation occurs long after the former has started to yield

No reversible $I_c$ reduction before irreversible stress limit of 177 MPa
CORC® wire has yielded significantly before $I_c$ degradation occurred
Stress-strain of CORC® wire former and tapes

These measurements will help us understand the stress-strain curve of a CORC® wire

2 mm wide tapes with 30 µm substrate

2.55 mm copper former

Yield stress (76 K, 0.2 % strain)
- Tapes: 1,092.7 MPa
- Former: 109.7 MPa
Comparing stress-strain curves of CORC® wires

Stress-strain dependence calculated with rule of mixtures (ROM)
- 27 or 30 tapes with Yield stress 1,092.7 MPa
- 2.55 mm thick former with Yield stress of 109.7 MPa

Large difference in CORC® wire Yield stress (0.2 %)
- ROM: 250 – 270 MPa
- Actual samples: 100 – 120 MPa

Difference explained by ROM assumes straight parallel tapes, while tapes in CORC® wire are springs

The REBCO tapes will only see high axial stresses once the former yields
Axial tensile stress fatigue of CORC® wires

Test procedure for cycling in liquid nitrogen

- Each sample is loaded to peak load responding to predetermined $I_c$ retention: 95 – 97 %, 80 %, and 60 %
- Load cycled between 10 % and 100 % of peak load

Source of the change in $I_c$ (decrease followed by recovery) during cycling unknown
Once real degradation occurs at stress exceeding the irreversible stress limit, $I_c$ falls off a cliff
Conclusions

Effect of transverse compressive load on CORC® cables and wires
- Effect of transverse compressive load on CORC® cable and wire \( I_c \) was determined at 76 K
- Larger gaps spacing between tapes and thicker copper plating on tapes decrease irreversible load limit
- Irreversible transverse compressive load limit of practical CORC® cables and wires depends on strain state of their tapes after winding
- Cyclic loading to 100,000 cycles doesn’t cause significant additional degradation at peak stress where retention of \( I_c \) is > 90%
- First estimate of critical transverse compressive stress: > 230 MPa

Effect of axial tensile stress on CORC® wires
- Effect of axial tensile stress on CORC® wire \( I_c \) has been determined at 76 K
- Critical stress of 30-tape CORC® wire with annealed copper former > 177 Mpa
- Critical stress can be increased by using harder temper copper in former
- \( I_c \) degradation occurs when CORC® wire has yielded significantly
- Stress cyclic to 100,000 cycles only affects \( I_c \) when peak stress much higher than irreversible stress limit
- Significant difference in failure mode between transverse compression and axial tension